Risk-Aware Cooperative Spectrum Access for Multi-Channel Cognitive Radio Networks

Ning Zhang, *Student Member, IEEE,* Nan Cheng, *Student Member, IEEE,* Ning Lu, *Student Member, IEEE,* Haibo Zhou, *Student Member, IEEE,* Jon W. Mark, *Life Fellow, IEEE,* Xuemin (Sherman) Shen, *Fellow, IEEE*

***Abstract*—In this paper, risk-aware cooperative spectrum access schemes for cognitive radio networks (CRNs) with multiple channels are proposed, whereby multiple primary users (PUs) operating over different channels choose trustworthy secondary users (SUs) as relays to improve throughput, and in return SUs gain transmission opportunities. To study the multi-channel cooperative spectrum access, cooperation over single channel is investigated first, which involves a PU selecting the suitable SU and granting a period of access time to the selected SU as a reward, considering trustworthiness of SUs. The above procedure is modeled as a Stackelberg game, through which access time allocation and power allocation are obtained. Based on the above results, cooperation over multiple channels is studied from the perspectives of the primary network and secondary network, respectively. Two schemes are proposed accordingly: the primary network-centric matching (PCM) scheme and the secondary network-centric cluster-based (SCC) scheme. In PCM scheme, cooperating SU for each channel is determined to maximize the total utility of the primary network, which is formulated as a maximum weight matching problem. In SCC scheme, SUs first form a cluster to share the channel state information (CSI), and the best SUs are selected for cooperation with PUs over different channels to obtain the maximum aggregate access time for the secondary network. Then, SUs share the obtained resource using congestion game and quadrature signalling. Numerical results demonstrate that, with the proposed schemes, PUs can achieve higher throughput, while SUs can obtain longer average access time, compared with the random channel access approach.**

***Index Terms*—Cognitive radio, stackelberg game, congestion game, maximum weight matching.**

I. INTRODUCTION

WITH the rapid growth in wireless applications and services, the demand for the spectrum is also rising dramatically, which is increasingly difficult to meet due to the scarcity of spectrum resources. Currently, spectrum is assigned to licensed users on a long term basis to avoid interference among different wireless systems. However, it is recognized that the licensed spectrum is underutilized since licensed users typically do not fully utilize their allocated spectrum most of the time [1] [2]. On the other hand, unlicensed users are being starved for spectrum availability. To cope with such a dilemma, cognitive radio has been introduced to enhance spectrum utilization by enabling unlicensed users to opportunistically utilize the spectrum bands [3]–[6]. In cognitive radio networking, licensed users and unlicensed users are referred to as primary users (PUs) and secondary users (SUs), respectively. Traditionally, SUs need to identify idle spectrum bands (or spectrum holes) via spectrum sensing before commencing transmission [7] [8]. However, spectrum sensing is energy-consuming and may not be accurate due to channel fading or shadowing. Moreover, the SU has to terminate the ongoing transmission once it detects that the spectrum band is re-occupied by a PU, making SU's transmissions highly dynamic [9] [10].

To deal with the aforementioned issues, cooperative spectrum access has been proposed in cognitive radio networks (CRNs) [11]–[16], whereby SUs cooperate with PUs to improve latter's transmission performance, and in return gain transmission opportunities. Therefore, both PUs and SUs can benefit from cooperation, which creates a win-win situation. With such cooperation between PUs and SUs, cognitive radio network has also been referred to as cooperative CRN (CCRN). Unlike the sensing based spectrum access, where SUs are transparent to PUs, the presence of SUs can be recognized by PUs in CCRN. In [11], the PU leases a fraction of access time to SUs in exchange for cooperation to increase the transmission rate, and during the rewarding time the SUs transmit simultaneously by selecting suitable transmission power. In [12], SUs cooperate to improve the PU's transmission rate and share the rewarding resource via a payment mechanism. A two-phase cooperation scheme is proposed in [13], whereby the PU transmits its signal to the SU in the first phase, and then the SU decodes the received signal and superimposes it with its own signal to broadcast in the second phase, using different power levels. In [16], different cooperation schemes are proposed, whereby the PU can cooperate with trustworthy SUs to enhance its security level and SUs can gain transmission opportunities.

However, all the above works only consider cooperation at the transmission link, i.e., one pair of PU and SU(s), which might not be sufficient to exploit the cooperation benefits in the whole network. This is because there exist multiple links in the network, which causes competition among PUs when they choose SUs. In [17], the authors consider multiple PUs performing cooperation with multiple SUs in the network, where the transmission of PUs are divided into different frames and different pairs of PU and SU perform cooperation over

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N. Zhang, N. Cheng, N. Lu, Jon W. Mark and X. Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L 3G1, Canada (e-mail:{n35zhang, n5cheng, n7lu, jwmark, sshen}@uwaterloo.ca).

H. Zhou is with the Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China (e-mail:haibozhou@sjtu.edu.cn).

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different frames. However, it is still limited to a single channel. In practice, a system usually consists of multiple channels, allowing users to communicate simultaneously. Therefore, a more realistic scenario is that cooperation among multiple PUs and multiple SUs could be performed over different channels simultaneously. However, the existing solutions might not be applicable, since they are designed either for one pair of PU and SU or multiple PUs and multiple SUs over one channel. Moreover, it is often assumed that SUs are well-behaved during cooperation. When there exist some dishonest users, or even malicious ones, those SUs can participate in cooperation, and hence cooperation may incur risks.

In this paper, we make an effort to facilitate cooperation for multi-channel CRNs, where PUs operating over different channels cooperate with SUs to improve throughput and grant rewarding access time to cooperating SUs for their own transmission. To study the multi-channel case, cooperation over single channel is studied first, which is modeled by Stackelberg game. To evaluate the risk of cooperation with certain SU, the concept of trust value is integrated into the game. By analyzing such a game, the cooperation parameters for a pair of PU and SU can be obtained, e.g., the access time allocation coefficient of the PU and the optimal transmission power of the SU. Based on the outcome of the Stackelberg game, cooperation over multiple channels in the network is studied to maximize the total network utility from different perspectives. From the perspective of the primary network, the objective is to maximize the PUs' aggregate throughput of different channels. From the perspective of the secondary network, the objective is to maximize the aggregate rewarding access time of different channels. Two schemes are proposed accordingly: the primary network-centric matching (PCM) scheme and the secondary network-centric cluster-based (SCC) scheme. In PCM scheme, cooperating SUs over each channel are determined to maximize the total utility of the primary network, which is formulated as a maximum weight matching problem. In SCC scheme, to better exploit transmission opportunities, SUs first form a cluster based on geographic locations, perform cooperation with PUs to obtain the transmission opportunities over different channels using the approach for single channel case, and then share them. To obtain the maximum aggregate access time, the best SUs for cooperation with PUs over different channels are determined using maximum weight matching. To share the obtained access channels with different rewarding time fairly, SU follows an approach using congestion game and quadrature signalling. Specifically, *active SUs*, which participate in cooperation with PUs as relays, stay in the current operating channel and employ the in-phase component of quadrature amplitude modulation (QAM) for transmission; while *inactive SUs*, i.e., other SUs which are not selected as relays, choose access channels for their own interests by following Nash Equilibrium (NE) of the congestion game and employ the quadrature component of QAM for transmission. By employing quadrature signalling, the active and inactive SUs can access channels simultaneously without interference with each other [18]. With congestion game, each inactive SU can gain certain transmission opportunities, and more importantly, in a fair way.

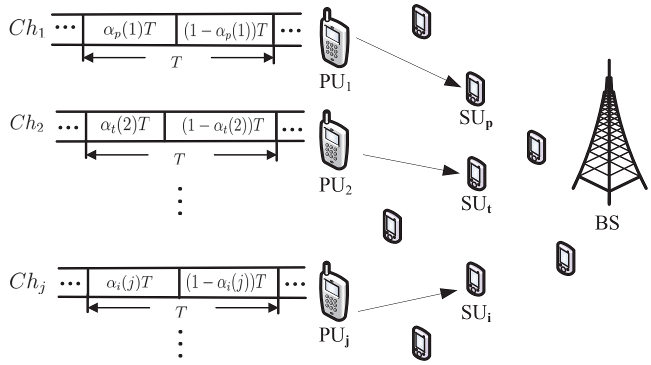

Figure 1. Cooperative cognitive radio network with multiple channels

The contributions of this work can be summarized as follows. First, we study cooperation for multi-channel CRNs; and we argue that the existing single channel results are inefficient when applying to multi-channel scenarios. Second, we integrate the trustworthiness of SUs in the cooperation to facilitate the design of risk-aware schemes. Third, cooperation over multiple channels is studied to maximize the total utility of the primary network using maximum weight matching. Finally, a cluster-based approach for SUs to exploit transmission opportunities over multiple channels is proposed, which integrates congestion game with quadrature signalling for cluster members to access the rewarding resource.

The remainder of the paper is organized as follows. The detailed description of the system model is given in Section II. Cooperation over single channel and multiple channels are studied in Section III and Section IV, respectively. Concluding remarks are provided in Section V.

II. System Model

This section presents the details of the cooperative cognitive radio networking model under consideration, together with the main system parameters, shown in Table I.

A. MAC Layer

As shown in Fig. 1, the system consists of two components, the infrastructure-based primary network and the ad hoc secondary network. The primary network with multiple channels (K channels) allows K PUs to transmit data simultaneously. Each PU communicates with the base station (BS) over one channel in a time slot with length T, and the PU over a ceratin channel can be indicated by the channel index, e.g., PU_j denotes the PU operating over channel j, where $j \in \{1, 2, ..., K\}$. In the secondary network, SUs transmit data to the corresponding receivers. Motivated by the poor quality of the primary link or large volume of data transmission requirement, PUs may seek for the opportunities to cooperate with SUs to increase the throughput. For cooperation, one PU selects one SU as a relay which adopts the Amplify-and-Forward (AF) mode [19] to forward the PU's message to improve the throughput[1]. In return, the PU grants a period

[1]The analysis for Decode-and-Forward (DF) mode is similar to that of AF mode. Hence, we only focus on AF cooperative scheme in the paper.

Table I
THE MAIN NOTATIONS.

Symbol	Description
$\mathcal{N}$	The set of SUs in the cluster, $\lvert\mathcal{N}\rvert = N$
$\mathcal{M}$	The set of inactive SUs in the cluster, $\lvert\mathcal{M}\rvert = M$
$\mathcal{K}$	The set of channels in the network, $\lvert\mathcal{K}\rvert = K$
$\alpha_i(j)$	The access time allocation coefficient when the PU on channel j cooperates with SU_i
$U_p^i(j)$	The utility function of the PU on channel j when cooperating with SU_i in Stackelberg game
$U_s^i(j)$	The utility function of SU_i when cooperating with the PU on channel j in Stackelberg game
$P_c^i(j)$	The transmission power of the PU on channel j when cooperating with SU_i
$h_{ps}^i(j)$	The channel gain from PU_j to SU_i
$h_{pb}(j)$	The channel gain from PU_j to the base station
h_{sb}^i	The channel gain from SU_i to the base station
h_s^i	The channel gain from SU_i to the corresponding secondary receiver
P_s^i	The transmission power of SU_i
Tr_i	The trust value of SU_i
Ψ_i	The duration of the rewarding access time of channel i
U_i^j	The utility of SU_i in the congestion game
n_i	The total number of inactive SUs choosing channel i in congestion game
$\zeta(n_i)$	The share of channel i which each SU selecting that channel can obtain
$n(S)$	The congestion vector corresponding to strategy profile S

of access time as a reward to the cooperating SU. Specifically, for a given channel, e.g., channel j, the cooperation between PU_j and SU_i is carried out in the following way. A fraction $\alpha_i(j)$ of the time slot duration T ($0 < \alpha_i(j) \leq 1$) is used for cooperative communication. Note that for $\alpha_i(j)$, i corresponds to SU_i and j corresponds to channel j or PU_j. In the first duration of $\frac{\alpha_i(j)T}{2}$, PU_j transmits data to SU_i, and in the subsequent duration of $\frac{\alpha_i(j)T}{2}$, SU_i relays the received data to BS. In the last period of $(1-\alpha_i(j))T$, which is the rewarding time, the cooperating SU_i transmits its own data to the corresponding secondary receiver. A common control channel is assumed for exchanging information among PUs, SUs, and BS (e.g., CSI), and for delivering the decision of the PUs to the secondary network.

B. Physical Layer

The channels between nodes are modeled as rayleigh block-fading channels, constant within each slot and varying over different slots. The channel gains from PU_j to BS, from PU_j to SU_i, from SU_i to BS, and from SU_i to its corresponding secondary receiver are denoted by $h_{pb}(j)$, $h_{ps}^i(j)$, h_{sb}^i, and h_s^i, respectively. Similar to [11]–[13], [20], the channel state information (CSI) is assumed available in the system, which can be obtained by periodical pilots. The bandwidth for each channel is W. For cooperation, PU_j chooses power $P_c^i(j)$ for the transmission from PU_j to SU_i. SU_i is constrained to spend the same power P_s^i for both the cooperation and its own transmission so as to ensure that SU_i spends at least the same power for cooperation as which it is willing to spend for its own transmission. The one-sided power spectral density of the independent additive white Gaussian noise is N_0.

C. Security Threats

If all the SUs are well-behaved, both PU and SU can benefit from their cooperation. However, when there exist some dishonest or malicious SUs, the normal operation of CCRN cannot be guaranteed. Specifically, the following security issues arising in CCRN need to be considered.

During cooperation, the malicious SUs can alter the packets from the PU or fabricate packets and then forward them to the destination. A legitimate SU may be compromised and misbehaves when it is selected to cooperate with the PU, e.g., it may launch black or grey hole attack, etc. A dishonest SU may not obey the cooperation rule during cooperation to pursue more self-benefits, e.g., it may transmit its own packets instead of relaying the packets from the PU. Moreover, considering the mobility of SUs, the malicious or dishonest SUs may misbehave at one place and then move to other places. Since there is no record of the past behaviors, these users can have the same opportunity to be selected to cooperate with the PU, and then continue to harm the system. As a summary, we list the potential misbehaviors in CCRN as follows.

1) Selfishness: the cooperating SU may choose a lower transmission power than the expected one during cooperation or it just chooses not to forward the PU's message to save energy.
2) Maliciousness: the malicious SU may delete, modify or replace the bits in the DF mode. In AF mode, it may intentionally add some jamming signals to corrupt the PU's signal.
3) Dishonesty: the dishonest SU may provide fake CSI to gain transmission opportunities.

Without considering these security threats, the PU may choose an untrustworthy SU for cooperation, which may cause the failure of cooperation and degrade the QoS of PUs.

III. Cooperation over Single Channel

In this section, we will discuss the cooperation between a PU and an SU over channel j. Since we focus on a single channel, for ease of presentation, the channel indices in related notations are omitted, e.g., $\alpha_i(j)$ becomes α_i, $h_{ps}^i(j)$ becomes h_{ps}^i, and so on. Due to the poor channel condition or the traffic requirement, the PU may desire higher throughput which the direct transmission cannot achieve. In this case, the PU can choose an SU to act as a cooperating relay to increase its throughput, while in return grant a period of access time to the SU. Therefore, the cooperation can be performed on a basis of mutual benefits, where the PU can increase its throughput while the SU can gain transmission opportunities. To evaluate the risks of cooperation, trust value is applied and the above cooperation procedure is modeled using Stackelberg game. In such a game, the utilities of both the PU and the SU are presented and analyzed. By analyzing the game, the close-form solutions for the players' best strategies are derived, which constitute the Stackelberg equilibrium.

A. Trust Computational Model

In an unfriendly environment, the aforementioned security issues may rise, which cannot be well mitigated by means of cryptographic methodologies [21]. Thus, trust and reputation system is applied to address these issues [22]. Specifically, trust values are assigned to SUs and utilized to evaluate the behaviors of SUs. The primary system maintains a table for recording identities and the corresponding trust values of its one-hop neighboring SUs. In addition, BS keeps the trust values of all SUs in its domain. Each time after cooperation, the behavior of the selected SU will be evaluated and the trust value will be updated accordingly. Then, the trust value will be exchanged periodically between the PUs and the BS.

We use a Bayesian framework [23] [24] to evaluate the trust values: each entity is assumed to behave well with probability p, and misbehave with probability $(1-p)$, i.e., the behavior of the entity follows a Bernoulli distribution. Through a series of observations, a posteriori probability can be derived to estimate the future behaviors of the entity. Posteriori probabilities of binary events can be represented as the beta distribution. An expression of the probability density function (PDF) $f(\hat{p}|\kappa,\iota)$ in terms of the gamma function Γ is given by:

$$f(\hat{p}|\kappa,\iota)=\frac{\Gamma(\kappa+\iota)}{\Gamma(\kappa)\cdot\Gamma(\iota)}\cdot\hat{p}^{(\kappa-1)}\cdot(1-\hat{p})^{(\iota-1)}, \quad (1)$$

where $\hat{p}$ is the estimate of p, and κ, ι are the two parameters. The expectation of beta distribution is given by $E(\hat{p})=\frac{\kappa}{(\kappa+\iota)}$, which can be used to represent the trust value of the relevant entity.

In our system, a malicious or dishonest SU_i behaves well with probability p_i and misbehaves with probability $1-p_i$. In order to estimate the trustworthiness of SUs, BS needs to observe the ongoing transmission and evaluate the activities of SUs according to the received signals. To determine whether the relaying SU misbehaves or not, one approach is to utilize tracing symbols, which are known at both the source and the destination [25] [26]. Another way is based on the correlation between signals received from the source and the relay [27]. In addition, the misbehavior can also be detected based on the success or failure of transmitted frames via acknowledgment (ACK/NACK) [28]. Based on existing works in the literature, it is assumed that the misbehavior of relaying nodes can be detected. Consider a process with two possible outcomes (misbehavior or well-behavior), and let μ and ν be the observed number of good behaviors and misbehaviors, respectively. Then, the PDF of observing outcomes in the future can be expressed as a function of past observations by setting: $\kappa=\mu+1$ and $\iota=\nu+1$. Thus, the expected value of $\hat{p}$ can be determined from observations as follows:

$$E(\hat{p})=\frac{\mu+1}{(\mu+\nu+2)}, \quad (2)$$

which is used as the trust value Tr_i of SU_i.

When new observations of a particular SU are made, e.g., δ observed misbehaviors and ξ observed good behaviors, the associated trust value can be updated using (2) by setting $\nu:=\nu+\delta$ and $\mu:=\mu+\xi$.

B. Stackelberg Game between PU and SU

Since the primary user and secondary user are selfish and rational, they might not have a common objective, i.e., the PU and the SU are interested in maximizing their own utilities. Thus, game theory can be applied to model the interactions between the two users. Moreover, considering different priorities for spectrum usage of PUs and SUs, Stackelberg game is most suitable to model the cooperation procedure. In the Stackelberg game, the PU acts as the leader and the SU acts as the follower. As the leader, the PU can choose the best strategies, aware of the effect of its decision on the strategies of the follower (the SU); while the SU can just choose its own strategies given the selected parameters of the PU. The utility functions for both PU and SU are respectively defined in the following. By analyzing the game, the best cooperating SU and the optimal cooperation parameters can be determined.

1) Primary User: Given a fixed time duration T, increasing the throughput is equivalent to increasing the average transmission rate. To this end, the PU selects the most suitable SU from the set $\mathbf{S}_p$ of its one-hop neighbors. Suppose that SU_i is chosen for cooperation, the PU decides the slot allocation parameter α_i and its transmission power P_c^i to maximize the potential profit, on the basis of available instantaneous CSI.

Without cooperation, the transmission rate of the direct communication can be given by

$$R_d=W\log_2(1+\frac{P\left|h_{pb}\right|^2}{N_0}). \quad (3)$$

For cooperation, the transmission rate R_c^i through AF cooperative communication between the PU and SU_i is given as follows:

$$R_c^i=\frac{\alpha_i W}{2}\log_2[1+\frac{P_c^i\left|h_{pb}\right|^2}{N_0}+f(P_c^i\left|h_{ps}^i\right|^2,P_s^i\left|h_{sb}^i\right|^2)], \quad (4)$$

where

$$f(P_c^i\left|h_{ps}^i\right|^2,P_s^i\left|h_{sb}^i\right|^2)=\frac{1}{N_0}\frac{P_c^i\left|h_{ps}^i\right|^2P_s^i\left|h_{sb}^i\right|^2}{P_c^i\left|h_{ps}^i\right|^2+P_s^i\left|h_{sb}^i\right|^2+N_0}.$$

The factor $\frac{\alpha_i}{2}$ accounts for the fact that $\alpha_i T$ is used for cooperative relaying, which is further split into two phases. The PU chooses cooperation only when the transmission rate via cooperation is greater than that of the direct communication. Considering the trust value Tr_i of each neighboring SU_i, the utility function is given by

$$U_p^i = Tr_i \cdot R_c^i, \tag{5}$$

which indicates the expected transmission rate the PU can achieve through cooperation with SU_i. The objective of the PU is to maximize its utility function and the strategy is to choose the most suitable SU from the set of its one-hop neighboring SUs and the cooperation parameters, i.e., the slot allocation parameters α_i and the transmission power P_c^i for cooperation with the selected SU_i.

2) Secondary User: The SU can gain transmission opportunities through cooperation with the PU. In particular, the SU relays PU's data in the second phase and transmits its own data in the last phase. Assuming cooperation with the PU, the selected SU_i decides its transmission power, pertaining to the given α . The target of the SU is to maximize throughput (equivalent to the transmission rate) without expending too much energy. Following the cooperation agreement, SU_i spends the same power P_s^i for both cooperative and secondary transmissions. In particular, the transmission rate R_s^i for secondary transmission between SU_i and its corresponding receiver is given by

$$R_s^i(\alpha_i) = (1-\alpha_i)W\log_2(1+\frac{P_s^i\left|h_s^i\right|^2}{N_0}). \tag{6}$$

With energy consumption $P_s^i(1-\frac{\alpha_i}{2})T$, the utility function of SU_i can be represented by $R_s^i(\alpha_i)T - c\cdot P_s^i(1-\frac{\alpha_i}{2})T$, where c $(0<c<1)$ is the weight of energy consumption in the overall utility. With a smaller c, the SU values throughput more than energy consumption, and vice versa. Over the period of T, the utility function of SU_i is given by

$$U_s^i(\alpha_i) = \quad W\log_2(1+\frac{P_s^i\left|h_s^i\right|^2}{N_0})(1-\alpha_i) - c(1-\frac{\alpha_i}{2})P_s^i. \tag{7}$$

The objective of SU_i in the game is to maximize its utility by choosing the optimal transmission power P_s^i.

C. Game Analysis

As a sequential game, the Stackelberg game can be analyzed by the backward induction method. First, the optimal strategy of the SU (the follower) is analyzed, assuming the strategy of the PU (the leader) is fixed. Second, the PU decides the optimal strategy, aware of the outcomes of the first step. By doing so, the best response functions of both the PU and the SU are derived such that the corresponding utilities can be maximized. Then, the Stackelberg equilibrium of the proposed game can be achieved based on the best response functions.

1) Best Response Function of the SU: Assuming that the PU uses α_i for cooperation, SU_i selects the optimal transmission power to maximize its utility, which can be formulated as the following optimization problem:

$$\max_{P_s^i} U_s^i(\alpha_i) = (1-\alpha_i)W\log_2(1+\frac{P_s^i\left|h_s^i\right|^2}{N_0}) - c(1-\frac{\alpha_i}{2})P_s^i$$

s.t. $0 \le P_s^i \le P_{max}$, where P_{max} is the power constraint for SU_i. Solving the above problem, the optimal transmission power can be determined.

Definition 1: Let $P_s^{*i}(\alpha_i)$ be the best response function of the secondary user if the utility of SU_i can achieve the maximum value when $P_s^{*i}(\alpha_i)$ is selected, for any given α_i, i,e., $\forall\ 0<\alpha_i<1$, $U_s^i(P_s^{*i}(\alpha_i),\alpha_i) \ge U_s^i(P_s^i(\alpha_i),\alpha_i)$.

Theorem 1: The best response function of the secondary user $P_s^{*i}(\alpha_i)$ is given by $P_s^{*i}(\alpha_i) = \min\{\frac{(1-\alpha_i)W}{c(1-\frac{\alpha_i}{2})\ln 2} - \frac{N_0}{|h_s^i|^2}, P_{max}\}$, when the primary user selects a certain α_i for cooperation.

Proof: Given the time allocation coefficient α_i, the utility function of SU_i is given as follows:

$$U_s^i(\alpha_i) = (1-\alpha_i)W\log_2(1+\frac{P_s^i\left|h_s^i\right|^2}{N_0}) - c(1-\frac{\alpha_i}{2})P_s^i. \tag{8}$$

From the above equation, it is easy to prove that the utility function first increases and then decreases with the increase of P_s^i without considering the power constraint. Therefore, there exists an optimal power such that U_s^i can reach the maximum value at that transmission power. Taking the first order partial derivative of the utility function with respect to P_s^i yields

$$\frac{\partial U_s^i}{\partial P_s^i} = \frac{(1-\alpha_i)W\left|h_s^i\right|^2}{(1+\frac{P_s^i h_s^{i2}}{N_0})N_0\ln 2} - c(1-\frac{\alpha_i}{2}). \tag{9}$$

Setting $\frac{\partial(U_s^i)}{\partial(P_s^i)} = 0$ yields the optimal transmission power, which is given by

$$\frac{(1-\alpha_i)W}{c(1-\frac{\alpha_i}{2})\ln 2} - \frac{N_0}{|h_s^i|^2}. \tag{10}$$

Taking the power constraint into consideration, the best response function $P_s^{*i}(\alpha_i)$ will be

$$P_s^{*i}(\alpha_i) = \min\{\frac{(1-\alpha_i)W}{c(1-\frac{\alpha_i}{2})\ln 2} - \frac{N_0}{|h_s^i|^2}, P_{max}\}. \tag{11}$$

This completes the proof. ■

The first order derivative of the best response function with respect to α_i is given by $\frac{-\alpha_i W}{(-2+a)^2 c\ln 2)}$, which is negative. Therefore, the best transmission power of SU_i is a decreasing function of α_i. It is explained by that the SU is willing to spend more transmission power during cooperation if the PU allocates more time for the SU's transmission.

2) Best Response Function of the PU: Aware of the best response function of the SU, the PU decides its own best strategy for utility maximization. Thus, the best response function can be derived by solving the following optimization problem:

$$\max_{\alpha_i, P_c^i, i}\ \frac{\alpha_i W}{2}\log_2[1+\frac{P_c^i|h_{pb}|^2}{N_0} + f(P_c^i\left|h_{ps}^i\right|^2, P_s^i\left|h_{sb}^i\right|^2)]$$

$$\text{s.t. } 0 < P_c^i \le P_{max}, 0<\alpha_i\le 1, SU_i \subseteq \mathbf{S}_p.$$

Definition 2: Let $\alpha^*, P_c^{*i^*}, i^*$ be associated with the best response function of the primary user if the utility of the PU can achieve the maximum value when this strategy is selected.

Theorem 2: The best response function of the primary user $\alpha^*, P_c^{*i^*}, i^*$ can be given by $(\alpha^*, P_c^{*i^*}, i^*) = \arg\max_{\alpha_i, P_c^i, i} U_p^i$. In particular, $i^* = \arg\max U_p^i(P_c^{*i}, \alpha_i^*)$, where

$$P_c^{*i} = P_{max}$$

$$\alpha_i^* = \begin{cases} (15), \text{ if } \frac{W}{c\ln 2} - \frac{N_0}{|h_s^i|^2} < P_{max} \\ \max\{2+\frac{2}{\frac{c\ln 2}{W}(P_{max}+\frac{N_0}{|h_s^i|^2})-2}, (15)\}, \text{ otherwise} \end{cases} \tag{12}$$

P_c^{*i} and α_i^* are the optimal transmission power and time allocation coefficient respectively, assuming cooperation with SU_i. The optimal $P_c^{*i^*}$ and α_i^* correspond to the selected i^*.

Proof: Since the first order derivative of the utility function with respect to P_c^i is always positive, U_p is a monotonically increasing function as P_c^i increases. Moreover, considering the parameters P_c^i and α_i are independent, P_c^i should be selected as the maximum power so that the utility can reach the maximum value. Therefore, to solve the optimization problem, it is equivalent to optimize the utility function when $P_c^i = P_{max}$ and SU_i selects the best response $P_s^{*i}(\alpha_i)$. Since the first term in (11) monotonically decreases with respect to α_i, its maximum value is $\frac{W}{c\ln 2} - \frac{N_0}{|h_s^i|^2}$.

When $\frac{W}{c\ln 2} - \frac{N_0}{|h_s^i|^2} < P_{max}$, $P_s^{*i}(\alpha_i)$ always takes the value of the first term in (11). Substituting $P_c^i = P_{max}$ and $P_s^{*i}(\alpha_i) = \frac{(1-\alpha_i)W}{c(1-\frac{\alpha_i}{2})\ln 2} - \frac{N_0}{|h_s^i|^2}$ into the utility function of PU, the utility can be expressed by

$$U_p^i = \frac{\alpha_i W}{2}\log_2[1 + \frac{P_{max}\left|h_{pb}\right|^2}{N_0} + f(P_{max}\left|h_{ps}^i\right|^2, P_s^{*i}(\alpha_i)\left|h_{sb}^i\right|^2)], \tag{13}$$

which is a function of α_i. The first order derivative of (13) is given by

$$\frac{\partial U_p^i}{\partial \alpha_i} = A\cdot\alpha_i^2 + B\cdot\alpha_i + C, \tag{14}$$

where

$$\begin{aligned} A =& P_{max}\left|h_{ps}^i\right|^2 c + 2W\left|h_{sb}^i\right|^2 + N_0 c \\ B =& -2P_{max}\left|h_{ps}^i\right|^2 c - 4W\left|h_{sb}^i\right|^2 - 2N_0 c = -2\cdot A \\ C =& 2W\left|h_{sb}^i\right|^2. \end{aligned}$$

To find the optimal α_i^* such that U_p can be maximized, set first order derivative of (13) equal to 0. Since $C < A$, we have $B^2 - 4AC > 0$. Thus, the above quadratic function has real root(s). Considering the range of α_i ($0 < \alpha_i < 1$), there exists one and only one root α_r. The optimal α_i^* is given by

$$\begin{aligned} \alpha_i^* = \alpha_r &= 1 - \sqrt{1 - \frac{C}{A}} \\ &= 1 - \sqrt{1 - \frac{2W\left|h_{sb}^i\right|^2}{P_{max}\left|h_{ps}^i\right|^2 c + 2W\left|h_{sb}^i\right|^2 + N_0 c}} \end{aligned} \tag{15}$$

When $\frac{W}{c\ln 2} - \frac{N_0}{|h_s^i|^2} \geq P_{max}$, there exists α_0 in the range from 0 to 1, such that $P_s^*(\alpha_0) = P_{max}$. Specifically, $\alpha_0 = 2 + \frac{2}{D-2}$, where $D = \frac{c\ln 2}{W}(P_{max} + \frac{N_0}{|h_s^i|^2})$. The reason is that the range of D is from 0 to 1 due to the assumption that $\frac{W}{c\ln 2} - \frac{N_0}{|h_s^i|^2} \geq P_{max}$. For $\alpha_i \leq \alpha_0$, $P_s^{*i}(\alpha_i)$ always takes the value of P_{max}. Hence, U_p^i reaches the maximum value in that range when α_0 is chosen. For $\alpha_0 < \alpha_i \leq 1$, there exists one and only one root α_r for the above quadratic function, which is in the range from 0 to 1. If $\alpha_r < \alpha_0$, then $\frac{\partial U_p}{\partial \alpha_i} < 0$ when $\alpha_0 < \alpha_i \leq 1$. The derivative of U_p with respect to α_i is monotonically decreasing. Thus, the optimal $\alpha_i^* = \alpha_0$. Otherwise, the optimal $\alpha_i^* = \alpha_r$.

Based on the above analysis, the optimal α_i^* can be given as (12) in the theorem 2.

This completes the proof. ■

D. Existence of the Stackelberg Equilibrium

In this section, we prove that the solutions P_s^* in (11) and α^* in (12) are the Stackelberg Equilibrium. For this purpose, we discuss the two cases with/without considering the power constraint of the SU using the following properties. The detailed proof for the properties can be found in Appendix. Based on the properties, we first prove the existence of Stackelberg Equilibrium when the power constraint is not considered.

Property 1. The utility function U_s of the SU is concave with respect to its own power level P_s when the time allocation coefficient α is fixed.

For both cases, Property 1 always holds, which shows the concavity of the utility function of the SU. Due to Property 1, U_s is concave with respect to P_s. Without considering the power constraint, setting $\frac{\partial(U_s^i)}{\partial(P_s^i)} = 0$ yields the optimal transmission power P_s^*, which is given in (10). With P_s^* in (10), the SU can maximize its utility U_s.

For the case without considering the power constraint, we also have the following properties.

Property 2. For all SUs, the optimal transmission power P_s^* in (10) decreases with the time allocation coefficient α.

Property 3. The utility function of the primary user is concave with respect to the time allocation coefficient α, given that the optimal transmission power P_s^* of the SU in (10) is fixed.

Due to Property 2, there is a trade-off for the PU to select the time allocation coefficient α. When the PU allocates less time to the cooperating SU for transmission, the SU will choose a lower transmission power during cooperation, which results in a reduction in the utility of the PU. When the PU allocates more time for the SU, the PU will have less time for its own transmission, which may also lead to a decrease in its utility. In other words, the PU cannot keep increasing its utility by increasing α.

Due to Property 3, the optimal α can be obtained by setting $\frac{\partial U_p}{\partial \alpha} = 0$, since the utility function of the PU is concave with respect to α. Therefore, the PU can always find its optimal time allocation coefficient α^* in (15) such that $U_p(\alpha^*) \geq U_p(\alpha)$. Together with Property 1, given the time allocation coefficient α, the SU can always find its optimal transmission power P_s^* in (10). Then, P_s^* in (10) and α^* in (15) are the Stackelberg Equilibrium.

In the following, we will discuss the case with power constraint. Due to Property 2, P_s^* in (10) increases as α decreases. For a given value of α, P_s^* may achieve its maximum value P_{max}. Since the scenario before P_s^* approaches P_{max} is the same as the case without power constraint, we only discuss the case when $P_s^* = P_{max}$. When the SU chooses P_{max}, it is optimal for the PU to choose α_0, as in the analysis of α^* in Section III-C2. Therefore, we conclude that the solutions P_s^* in (11) and α^* in (12) are the Stackelberg Equilibrium.

E. Numerical Results

In this part, we present numerical results so as to provide insight into the proposed cooperative framework. Similar to [11], by normalizing the distance between PU and BS, the SU is approximately placed at the distance $d \in (0, 1)$ from the PU

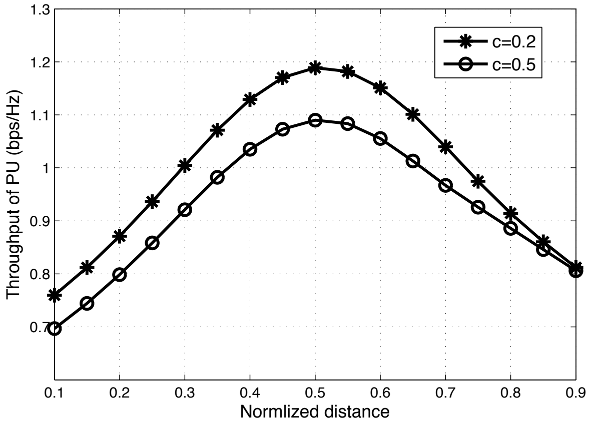

Figure 2. Throughput of PU, averaged over fading, versus the normalized distance d.

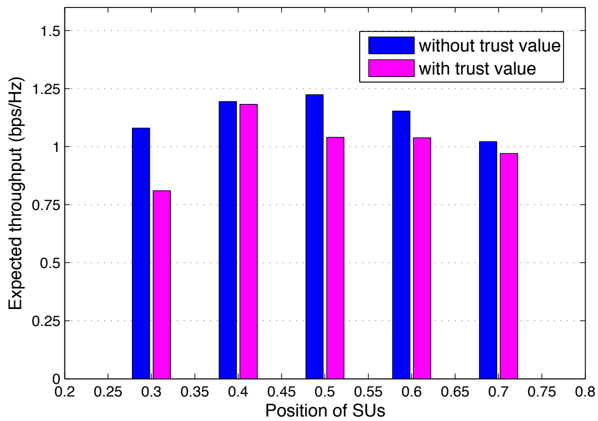

Figure 3. The impact of trust value on SU selection.

and $1-d$ from the BS. Considering a path loss model, the average power gains between the PU and SU, and between the SU and BS, are $\left|h_{ps}^i\right|^2 = \frac{1}{d^\zeta}$ and $\left|h_{sb}^i\right|^2 = \frac{1}{(1-d)^\zeta}$, respectively, where $\zeta = 3.5$ is the path loss coefficient. Aiming at reducing the system parameters, the maximum secondary transmission power P_{max} is normalized to 1 and we choose $P_{max}/N_0 = 0$ dB.

Fig. 2 shows the the PU's throughput on certain channel, averaged over fading, versus the normalized distance d, for c = 0.2 and 0.5. It is seen that there exists a cooperation range in which the PU can cooperate with the SU to achieve a higher throughput than that of direct transmission. Further, a smaller weight c results in a larger cooperation range.

Fig. 3 shows the impact of trust values on the SU selection. A number of SU_i $(i = 1, 2, 3, 4, 5)$ with associated trust values 0.75, 0.99, 0.85, 0.9, and 0.95, are located at the normalized distances d = 0.3, 0.4, 0.5, 0.6, and 0.7, respectively. Without considering trust values, the PU should select SU_3 since the PU can achieve the highest throughput via cooperation with SU_3. Considering trust values of SUs, SU_2 is the best choice since the PU can attain highest expected throughput via cooperation with SU_2.

IV. Cooperation over Multiple Channels

For cooperation over multiple channels, which involves multiple PUs and SUs, the approach aforementioned for the single channel cannot bring the maximum benefit to the whole network because it only optimizes the interest of individual users. Therefore, it is necessary to consider the cooperation in the whole network to exploit the cooperation benefits. To this end, we study the cooperation over multiple channels in this section, from the perspectives of the primary network and secondary network, respectively. Two schemes are proposed accordingly: PCM scheme and SCC scheme, to better exploit the overall cooperation benefits in the whole network.

A. Primary Network-Centric Matching Scheme

From the perspective of the primary network, since the cooperation can be carried out between multiple PUs and multiple SUs simultaneously, there may exist competition among PUs when selecting SUs. Moreover, the best SU selection for one single channel might not be optimal for the whole primary network. Considering above, PCM scheme is proposed, with the objective of maximizing the total utility of the primary network, which is defined as the aggregate throughput of PUs over different channels. Note that the throughput of a ceratin channel is obtained when the PU over that channel cooperates with a certain SU using the Stackelberg Equilibrium strategy.

Specifically, as the central controller, the base station is considered to have the global information in its domain, e.g., CSI. With the information, the base station can guide the PUs to select the suitable SUs, with the objective of maximizing the total utility of the primary network. Consider that there are K PUs simultaneously operating over different channels and N SUs seeking for transmission opportunities. Denote by $I_{i,j}$ the indicator which indicates whether PU_j cooperates with SU_i or not. Then, we have

$$I_{i,j} = \begin{cases} 1 & \text{if } PU_j \text{ cooperates with } SU_i \\ 0 & \text{otherwise.} \end{cases} \tag{16}$$

Selecting SUs is equivalent to determining all the indicators $I_{i,j}$, where $i \in \{1, 2, ..., N\}$ and $j \in \{1, 2, ..., K\}$. Such a problem can be formulated as follows:

$$\begin{aligned} &\max \sum_{i=1}^{N} \sum_{j=1}^{K} I_{i,j} U_p^i(j) \\ &s.t. \sum_i I_{i,j} \le 1, \forall i = 1, 2, ..., N \\ &\sum_j I_{i,j} \le 1, \forall j = 1, 2, ..., K \\ &I_{i,j} \in \{0, 1\}, \forall i \in \{1, 2, ..., N\}, \forall j \in \{1, 2, ..., K\} \end{aligned} \tag{17}$$

Note that $U_p^i(j)$ is the utility of the PU on channel j when cooperating with SU_i, which is given by (5).

The above problem can be transformed into the maximum weight bipartite matching problem, which can be solved in polynomial time [29]. Fig. 4 shows the bipartite graph, where the weight $w_{i,j}$ on each edge represents the expected transmission rate, i.e., $U_p^i(j)$ in (5), if the corresponding PU_j and SU_i (represented by vertices) cooperate with each other. Finding

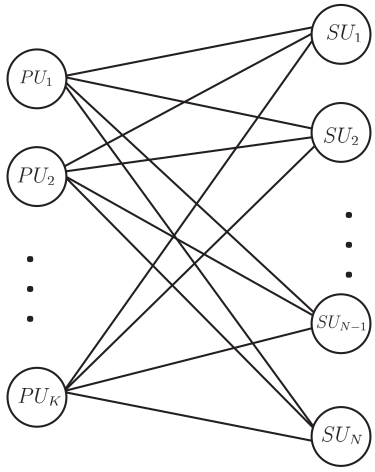

Figure 4. Bipartite graph for PCM scheme.

the optimal partner is equivalent to finding the maximum weight matching in Fig. 4. To solve the maximum weight bipartite matching problem, Hungarian algorithm [30] can be used which is a well known algorithm to find the matching such that the sum of the weights can be maximized. By doing so, the best matching can be found such that the aggregate throughput of the primary network is maximized.

B. Secondary Network-Centric Cluster-Based Scheme

From the perspective of the secondary network, for a certain SU, it can only select one channel one time to perform cooperation over that channel. It is possible that multiple SUs compete with each other over some channels to gain the transmission opportunities, while no suitable SUs exist to exploit the transmission opportunities over the other channels. Therefore, for the whole secondary network, the transmission opportunities are not efficiently utilized; for the individual SU, it is not guaranteed that the SU can gain the chance to access the channel since it also depends on other SUs selecting the same channel.

To exploit the transmission opportunities efficiently, SCC scheme is proposed with the objective of maximizing the total utility of the secondary network, which is defined as the aggregate rewarding access time of different channels. Note that the rewarding access time of a given channel is obtained when the SU cooperates with the PU over that channel using the Stackelberg Equilibrium strategy. Since the secondary network is ad hoc network, to maximize the total network utility and the average access time per user, SUs form a cluster and perform cooperation with PUs to gain transmission opportunities, and then share the obtained resource fairly.

Specifically, SUs first form a cluster $\mathcal{N}$ with the size of N based on the geographic locations, and contribute to share the information, e.g., CSI. Then, the best SUs can be selected for each channel to cooperate with PUs in order to obtain the maximum aggregate rewarding access time of different channels. To this end, a similar matching approach as in the previous section can be applied. The differences are as follows: i) the weights are the rewarding times, e.g., the corresponding weight is $(1-\alpha_i(j))T$, if SU_i chooses to cooperate with PU_j; and ii) the objective is to maximize the aggregate rewarding time by finding the best matching. After that, the selected SUs cooperate with the corresponding PUs to obtain the rewarding access time. Finally, SUs in the cluster share the obtained rewarding time fairly. To do this, SUs can be classified into two groups: active SUs (the selected SUs for performing cooperation with PUs as relays) and inactive SUs (with the size of M). Since active SUs devote the transmission power during cooperation, they should have a larger share of the rewarding time. To this end, two groups of users first share the resource using quadrature signaling, i.e., the active SUs stay in the current operating channel and use the in-phase component of QAM, while the inactive SUs select one channel to access and employ the quadrature component. By leveraging quadrature signaling, active and inactive SUs can transmit simultaneously without interference with each other [20]. Then, inactive SUs have to decide which channel to access to maximize their own utilities, i.e., the shares of rewarding time for accessing the channels. The decision process is modeled as a congestion game and the share that each inactive SU can obtain is determined by the Nash Equilibrium (NE) of the congestion game. By doing so, each SU can be guaranteed to gain certain access time. Moreover, the average access time obtained using the cluster based approach is longer than that using the random channel access approach, as shown in the numerical results.

Each inactive SU selects one channel to access among multiple channels with different rewarding time, to maximize its own utility. The decision process is modeled as a congestion game, which is defined by the tuple $\{\mathcal{M}, \mathcal{K}, (\sum i)_{i\in\mathcal{M}}, (U_j^i)_{i\in\mathcal{M}, j\in\mathcal{K}}\}$, where $\mathcal{M} = \{1, 2, ..., M\}$ denotes the set of inactive SUs, $\mathcal{K} = \{1, 2, ..., K\}$ denotes the set of channels, $\sum i$ represents the strategy space of SU_i, and U_i^j is the utility function of SU_i for selecting channel j. The utility function is a function of the total number of SUs choosing the same channel, which is a decreasing function due to competition or congestion. In other words, more SUs select the same channel, less share each SU can obtain. SUs aim to maximize its utility by deciding which channel to access and the utility function of SU_i can be given by

$$U_i^j = \Psi_j \zeta(n_j), \tag{18}$$

where Ψ_j is the duration of the rewarding time on channel j, $\zeta(n_j)$ is the share of the rewarding time on channel j which SU_i obtains, and n_j is the total number of inactive SUs choosing the channel j. Therefore, U_j^i represents the access time that SU_i obtains. For simplicity, the inactive SUs selecting the same channel share the rewarding time equally using TDMA, and then $\zeta(n_i) = 1/n_i$.

In the above congestion game, each SU chooses a single channel to access for maximizing its utility. If each one has chosen a strategy and no SU can increase its utility by changing strategy while the strategies of others keep unchanged, the current set of strategies constitutes an NE.

Definition 3: A strategy profile $S^* = (s_1^*, s_2^*, \ldots, s_M^*)$ is an NE if and only if

$$U_i(s_i^*, s_{-i}^*) \geq U_i(s_i', s_{-i}^*), \forall i \in \mathcal{M}, s_i' \in S_i, \tag{19}$$

where s_i and s_{-i} are the strategies selected by SU_i and all

Algorithm 1

// **Initialization**: Form the cluster based on geographic locations
// **Procedure 1**: Best SUs Selection
for each $SU_i \in \mathcal{N}$ **do**
  for PU_j on channel j, $j \in \mathcal{K}$ **do**
    Calculate access time allocation $\alpha_{i,j}$ using (12)
    Calculate rewarding periods $\Psi_{i,j} = 1 - \alpha_{i,j}$.
  end for
end for
Run Hungarian algorithm to find the best SUs for cooperation
// **Procedure 2**: Rewarding Access Time Sharing
Set congestion vector $n(S) = (n_1, ..., n_K) = (0, 0, ..., 0)$.
Order the rewarding periods on each channel $[\Psi_1, \Psi_2, \ldots, \Psi_K]$ decreasingly according to the length.
for each $SU_i \subseteq \mathcal{N}$ **do**
  if SU_i is active SU **then**
    SU_i stays in the current operating channel.
    SU_i employs the in-phase component for transmission.
  else
    for each Ψ_j, where $j \subseteq \mathcal{K}$ **do**
      Calculate $\Psi_j \zeta(n_j + 1)$.
    end for
    SU_i selects the channel with maximum $\Psi_j \zeta(n_j + 1)$.
    SU_i employs the quadrature component for transmission.
    $n_j = n_j + 1$.
  end if
end for
return

of its opponents, respectively. NE means no one can increase its utility unilaterally.

It is known that the congestion game always exists pure NE. The condition for NE in the congestion game can be given as follows:

$$n_i = \lceil \frac{\Psi_i M - \sum_{j \neq i, j \in \mathcal{K}} \Psi_j}{\sum_{j \in \mathcal{K}} \Psi_j} \rceil + n', \tag{20}$$

where $n' \in \{0, 1, 2, \ldots, \lceil \frac{\Psi_i M + \Psi_i (K-1)}{\sum_{k \in \mathcal{K}} \Psi_k} \rceil - \lceil \frac{\Psi_i M - \sum_{k \neq i, k \in \mathcal{K}} \Psi_k}{\sum_{k \in \mathcal{K}} \Psi_k} \rceil - 1\}$. The detailed proof can be found in [31]. Any strategy profile which satisfies the above condition in (20) will constitute an NE. However, there exist multiple NEs in our congestion game. In order for the SUs to select an NE strategy, the procedure 2 in algorithm 1 can be used for SUs to determine which channel to access.

The whole procedure of SCC scheme is presented in Algorithm 1, which consists of two main parts: the best SUs selection and rewarding access time sharing.

C. Numerical Results

Similar to the work in [32], we set up the simulation scenario as follows: The base station is located at the origin (0, 0) and PUs are randomly located between $(0, d_{p,min})$ and $(0, d_{p,max})$; while SUs are randomly located between $(0, d_{s,min})$ and $(0, d_{s,max})$. The number of PUs is set to 5. The distances between nodes are normalized by $d_{p,max}$ and the previous path loss model is utilized to calculate average power gains.

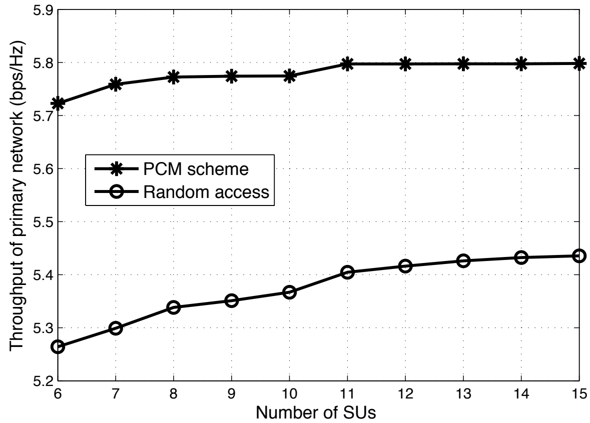

Figure 5. Throughput of the primary network averaged over fading versus number of SUs

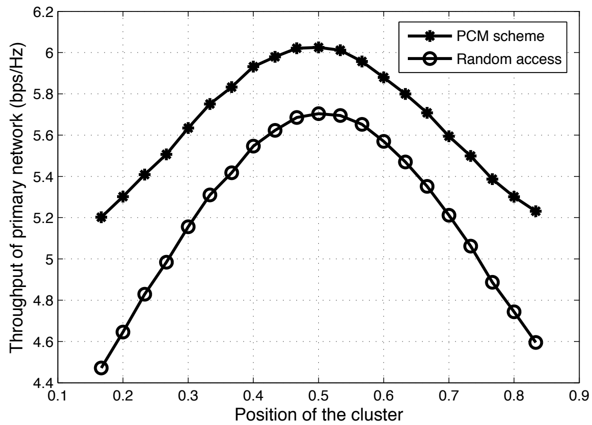

Figure 6. Throughput of the primary network, averaged over fading, versus the position of the cluster

Fig. 5 shows the throughput of the primary network, averaged over fading, versus the number of SUs where $d_{p,min} = 15$, $d_{p,max} = 20$, $d_{s,min} = 5$, and $d_{s,max} = 10$, respectively. It can be seen that the proposed scheme outperforms the random channel access approach whereby each SU randomly selects one channel to seek transmission opportunities through cooperation. The result of random access approach is obtained by Monte Carlo simulation consisting of 1000 trials.

Fig. 6 shows the throughput of the primary network, averaged over fading, with respect to the position of the cluster. We fix the range of the SUs' locations (i.e., $d_{s,max} - d_{s,min}$) and change $d_{s,min}$. The position is estimated by the relative distance from $d_{s,min}$ to $d_{p,min}$ normalized by $d_{p,max}$. It can be seen that the throughput first increases and then drops when the cluster moves closely to PUs. The reason is that when the cluster is too close to PUs, the channels between SUs and the base station become poor; and when the cluster is too far away from PUs, the channels between SUs and PUs are poor. As a result, the cooperation gain is limited.

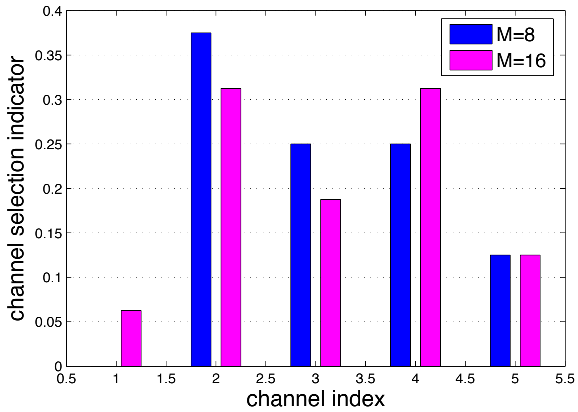

Figure 7. Impact of the number of inactive SUs on Nash Equilibrium

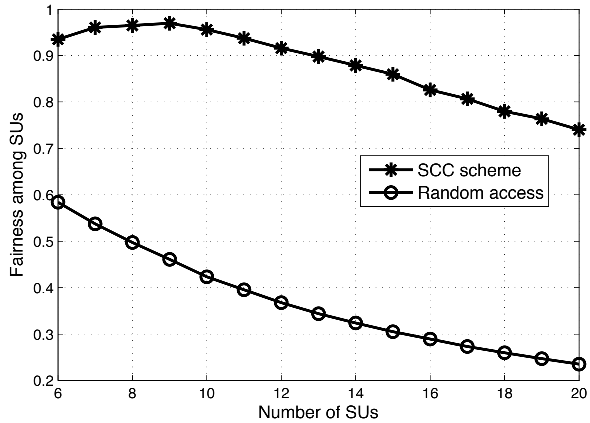

Figure 9. Fairness among SUs versus the number of SUs

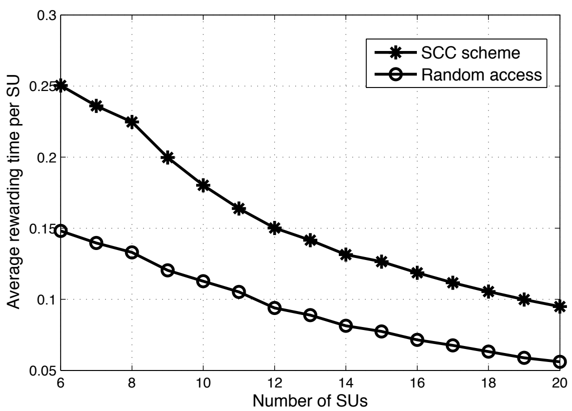

Figure 8. Average access time per SU averaged over fading for SCC scheme and random channel access

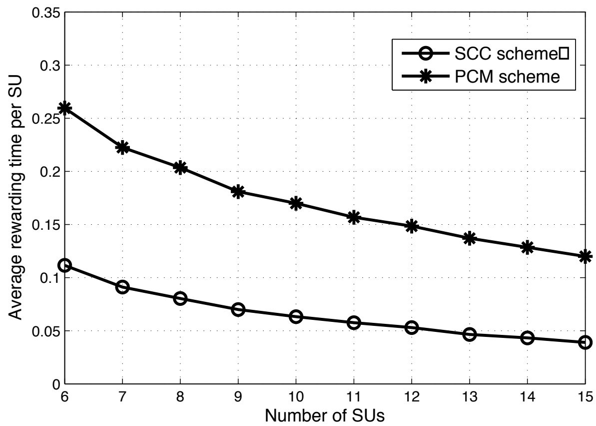

Figure 10. Average access time per SU averaged over fading for PCM scheme and SCC scheme

Fig. 7 shows the impact of the number of inactive SUs (M) on the NE of the congestion game. Define channel selection indicator of channel i as the number of inactive SUs choosing channel i divided by the total number of inactive SUs, i.e., n_i/M, which reflects the popularity of the channel. When M is small, some channel(s) may not be chosen by any SU. For example, there is no inactive SU choosing channel 1 when $M = 8$. When M becomes higher, all channels are selected by at least one SU and the selection indicator of each channel also changes to satisfy the NE condition.

Fig. 8 shows the average access time per user, averaged over fading, versus the size of the cluster. We compare the proposed scheme with the random channel access approach. It can be seen that each SU can obtain longer access time using the proposed scheme, compared with the random channel access approach.

Fig. 9 shows the fairness among SUs, averaged over fading. Similar to [33], the fairness is defined as $\frac{(\sum_i U_i)^2}{N \sum_i U_i^2}$, where U_i is the access time obtained by SU_i. It can be seen that the fairness of the proposed scheme outperforms the random access approach. This is because each SU can obtain a certain share of access time using SCC scheme, while only a few SUs can exclusively access the channel using the random channel access approach.

Fig. 10 shows the average access time per SU, averaged over fading, when using PCM scheme and SCC scheme, respectively. It reveals that the average access time using SCC scheme is greater than that using PCM scheme. The reason is that PCM scheme is based on the perspective of the primary network to maximize PUs' utility while SCC scheme aims to maximize SUs' utility.

V. Conclusions

In this paper, we have proposed risk-aware cooperative spectrum access schemes for multi-channel CRNs. We have studied cooperation on a single channel by Stackelberg game. Based on the results of the single channel scenario, we have proposed two schemes for the cooperation on multiple channels scenario, i.e., PCM scheme and SCC scheme, from the perspective of primary and secondary network, respectively. In PCM scheme, to maximize the total utility of the primary network, cooperating SU on each channel is determined using maximum weight matching. In SCC scheme, SUs form a cluster to maximize the total utility of the secondary network and share the obtained resources based on congestion game and quadrature signaling. Numerical results have demonstrated that, with the proposed schemes, the PUs can achieve higher throughput, while the SUs can obtain longer average access time, compared with the random channel access approach.

For future work, we will design a misbehavior detection mechanism dedicated to CCRN. In addition, we will exploit the channel statistic information to make the proposed scheme more efficient. The effect of imperfect CSI on cooperation will be studied as well.

Appendix

A. Proof of Property 1

Taking the first order partial derivative of the utility function with respect to P_s yields

$$\frac{\partial U_s}{\partial P_s} = \frac{(1-\alpha)W\left|h_s\right|^2}{(1+\frac{P_s h_s^2}{N_0})N_0 \ln 2} - c(1-\frac{\alpha}{2}). \tag{21}$$

Then, we have

$$\frac{\partial U_s^2}{\partial P_s^2} = -\frac{(1-\alpha)W\left|h_s\right|^4}{(1+\frac{P_s h_s^2}{N_0})^2 N_0^2 \ln 2}. \tag{22}$$

From the above equation, we can see that $\frac{\partial U_s^2}{\partial P_s^2} < 0$. Therefore, the utility function U_s^i of SU_i is concave in its own power level P_s^i when the time allocation is fixed.

B. Proof of Property 2

For a given SU, the optimal transmission power is given by

$$P_s^*(\alpha) = \frac{(1-\alpha)W}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{\left|h_s\right|^2}. \tag{23}$$

Taking the first derivative of P_s^* with respect to α, we have

$$\frac{\partial P_s^*}{\partial \alpha} = \frac{-\alpha W}{\left(-2+\alpha\right)^2 c \ln 2}. \tag{24}$$

The denominator is always positive, while the numerator is negative. Then, $\frac{\partial P_s^*}{\partial \alpha} < 0$. Therefore, the optimal transmission power P_s^* decreases with α.

C. Proof of Property 3

Since P_s^* is continuous with α, the utility function U_p of the PU is also continuous with α. Substituting $P_s^*(\alpha) = \frac{(1-\alpha)W}{c(1-\frac{\alpha}{2})\ln 2} - \frac{N_0}{|h_s|^2}$ into U_p, the utility can be given by (13), which is a function of α. Taking first order derivative of (13) withe respect to α yields (14). Then, taking second order derivative of (13) with respect to α yields

$$\frac{\partial^2 U_p}{\partial \alpha^2} = 2 \cdot A\alpha + B. \tag{25}$$

Since $A > 0$, $B = -2A$, and $0 < \alpha < 1$, we have $\frac{\partial^2 U_p}{\partial \alpha^2} < 0$. Therefore, the utility function of the primary user is concave in the time allocation coefficient α.

Acknowledgement

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Ning Zhang (S'12) received the B.Sc. degree from Beijing Jiaotong University and the M.Sc. degree from Beijing University of Posts and Telecommunications, Beijing, China, in 2007 and 2010, respectively. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. His current research interests include cooperative networking, cognitive radio networks, physical layer security, and vehicular networks.

Nan Cheng (S'13) is currently a Ph.D. candidate in the department of Electrical and Computer Engineering, the University of Waterloo, Waterloo, ON, Canada. He received his B.S. degree and M.S. degree from Tongji University, China, in 2009 and 2012, respectively. Since 2012, he has been a research assistant in the Broadband Communication Research group in ECE Department, the University of Waterloo. His research interests include vehicular communication networks, cognitive radio networks, and resource allocation in smart grid.

Ning Lu (S'12) received the B.Sc. and M.Sc. degrees from Tongji University, Shanghai, China, in 2007 and 2010, respectively. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. His current research interests include capacity and delay analysis, media access control, and routing protocol design for vehicular networks. Mr. Lu served as a Technical Program Committee Member for IEEE 2012 International Symposium on Personal, Indoor, and Mobile Radio Communications.

Haibo Zhou (S'11) received the M.Sc. degree in Information and Communication Engineering from University of Electronic Science and Technology of China, Chengdu, China, in 2007. He is currently pursuing his Ph.D degree in Shanghai Jiao Tong University, China. His current research interests include resource management and performance analysis in cognitive radio networks and vehicular networks.

Jon W. Mark (M'62-SM'80-F'88-LF'03) received the Ph.D. degree in electrical engineering from McMaster University in 1970. In September 1970 he joined the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, where he is currently a Distinguished Professor Emeritus. He served as the Department Chairman during the period July 1984-June 1990. In 1996 he established the Center for Wireless Communications (CWC) at the University of Waterloo and is currently serving as its founding Director. Dr. Mark had been on sabbatical leave at the following places: IBM Thomas J. Watson Research Center, Yorktown Heights, NY, as a Visiting Research Scientist (1976-77); AT&T Bell Laboratories, Murray Hill, NJ, as a Resident Consultant (1982-83): Laboratoire MASI, UniversitPierre et Marie Curie, Paris France, as an Invited Professor (1990-91); and Department of Electrical Engineering, National University of Singapore, as a Visiting Professor (1994-95). He has previously worked in the areas of adaptive equalization, image and video coding, spread spectrum communications, computer communication networks, ATM switch design and traffic management. His current research interests are in broadband wireless communications, resource and mobility management, and cross domain interworking.

Dr. Mark is a Life Fellow of IEEE and a Fellow of the Canadian Academy of Engineering. He is the recipient of the 2000 Canadian Award for Telecommunications Research and the 2000 Award of Merit of the Education Foundation of the Federation of Chinese Canadian Professionals. He was an editor of IEEE TRANSACTIONS ON COMMUNICATIONS (1983-1990), a member of the Inter-Society Steering Committee of the IEEE/ACMTRANSACTIONS ON NETWORKING (1992-2003), a member of the IEEE Communications Society Awards Committee (1995-1998), an editor of Wireless Networks (1993-2004), and an associate editor of Telecommunication Systems (1994-2004).

Xuemin (Sherman) Shen (IEEE M'97-SM'02-F'09) received the B.Sc.(1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering. He is a Professor and University Research Chair, Department of Electrical and Computer Engineering, University of Waterloo, Canada. He was the Associate Chair for Graduate Studies from 2004 to 2008. Dr. Shen's research focuses on resource management in interconnected wireless/wired networks, wireless network security, social networks, smart grid, and vehicular ad hoc and sensor networks. He is a co-author/editor of six books, and has published more than 600 papers and book chapters in wireless communications and networks, control and filtering. Dr. Shen served as the Technical Program Committee Chair/Co-Chair for IEEE Infocom'14, IEEE VTC'10 Fall, the Symposia Chair for IEEE ICC'10, the Tutorial Chair for IEEE VTC'11 Spring and IEEE ICC'08, the Technical Program Committee Chair for IEEE Globecom'07, the General Co-Chair for Chinacom'07 and QShine'06, the Chair for IEEE Communications Society Technical Committee on Wireless Communications, and P2P Communications and Networking. He also serves/served as the Editor-in-Chief for IEEE Network, Peer-to-Peer Networking and Application, and IET Communications; a Founding Area Editor for IEEE Trans. Wireless Communications; an Associate Editor for IEEE Trans. Vehicular Technology, Computer Networks, and ACM/Wireless Networks, etc.; and the Guest Editor for IEEE JSAC, IEEE Wireless Communications, IEEE Communications Magazine, and ACM Mobile Networks and Applications, etc. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004, 2007 and 2010 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. Dr. Shen is a registered Professional Engineer of Ontario, Canada, an IEEE Fellow, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, and a Distinguished Lecturer of IEEE Vehicular Technology Society and Communications Society.